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(54) Echo cancellers

(57) A full-duplex, two-wire Nyquist sampled data communication system includes an adaptive echo canceller (24) at each terminal (e.g., 10′). The echo canceller generates a replica (z_m) of the echo component of each sample (r_M) of the incoming signal. The replica and the sample are subtractively combined to provide an echo compensated signal (S_M). During intervals of simultaneous transmission and reception, i.e., double talk, the echo compensated signal may contain not only an uncancelled echo component but also a far-end data component. An adaptation error signal generator (80), operating in response to a stream of recovered data symbols (e.g., $\hat{a}_n$), estimates and removes the far-end data component from the echo compensated signal and, in response to the difference, generates an adaptation error signal (γE_{M-D}). This signal is applied as an error signal to the echo canceller. This allows the echo canceller to adapt its set of tap coefficients in response to the uncancelled echo component present in the echo compensated signal. Thus, stable and accurate echo cancellation results even during a double-talk interval.

FIG. 2

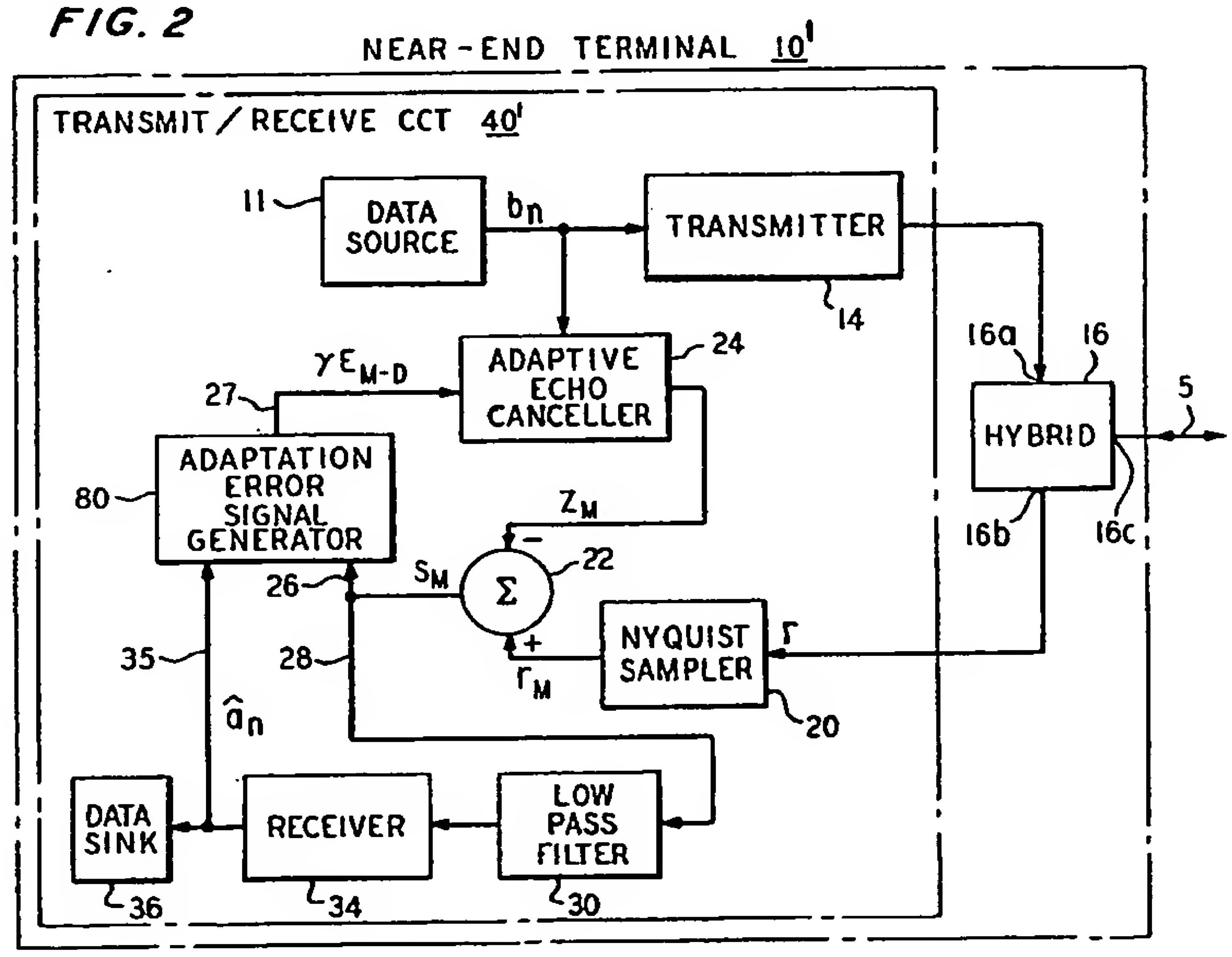

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FIG. 1
(PRIOR ART)

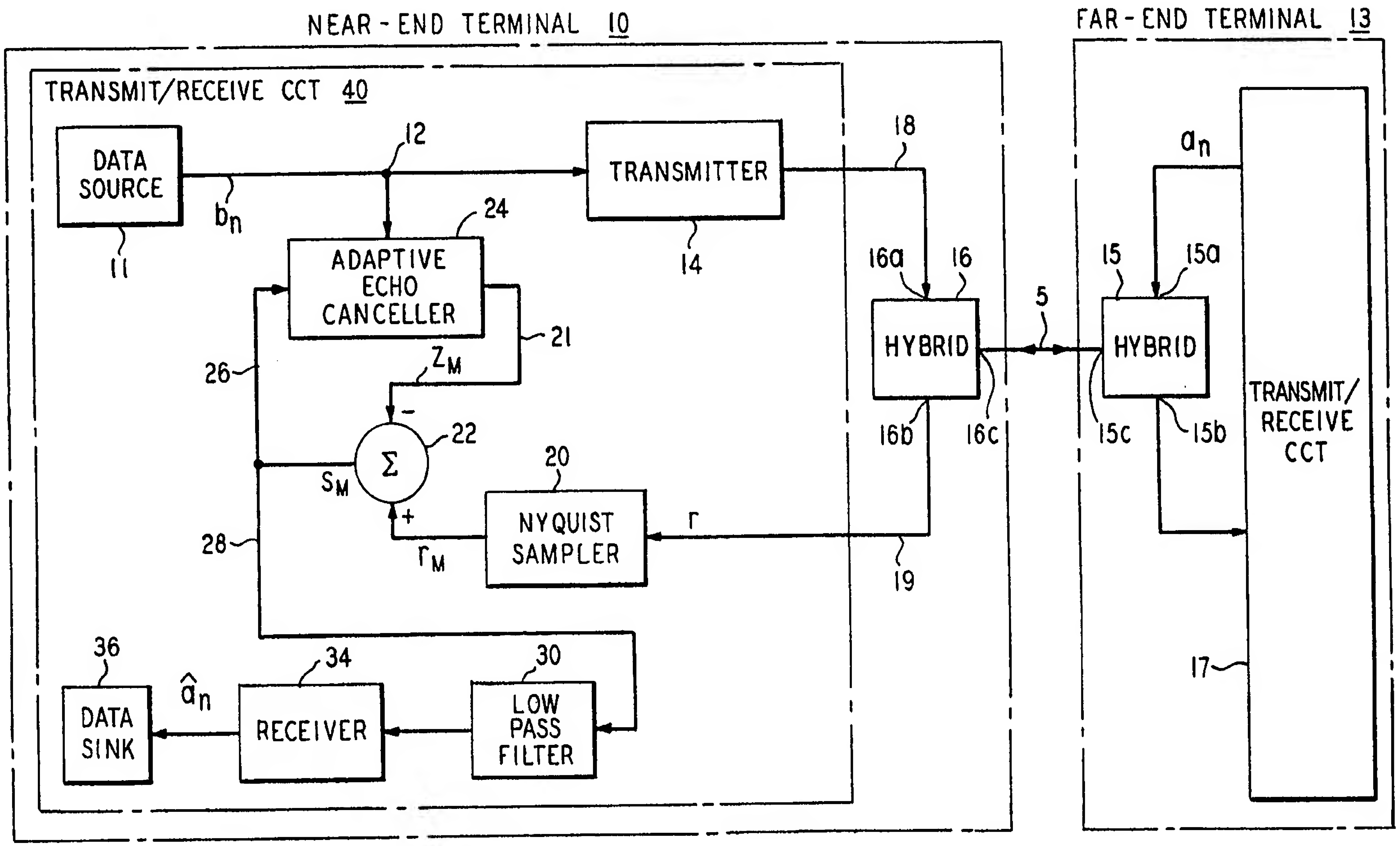


FIG. 2

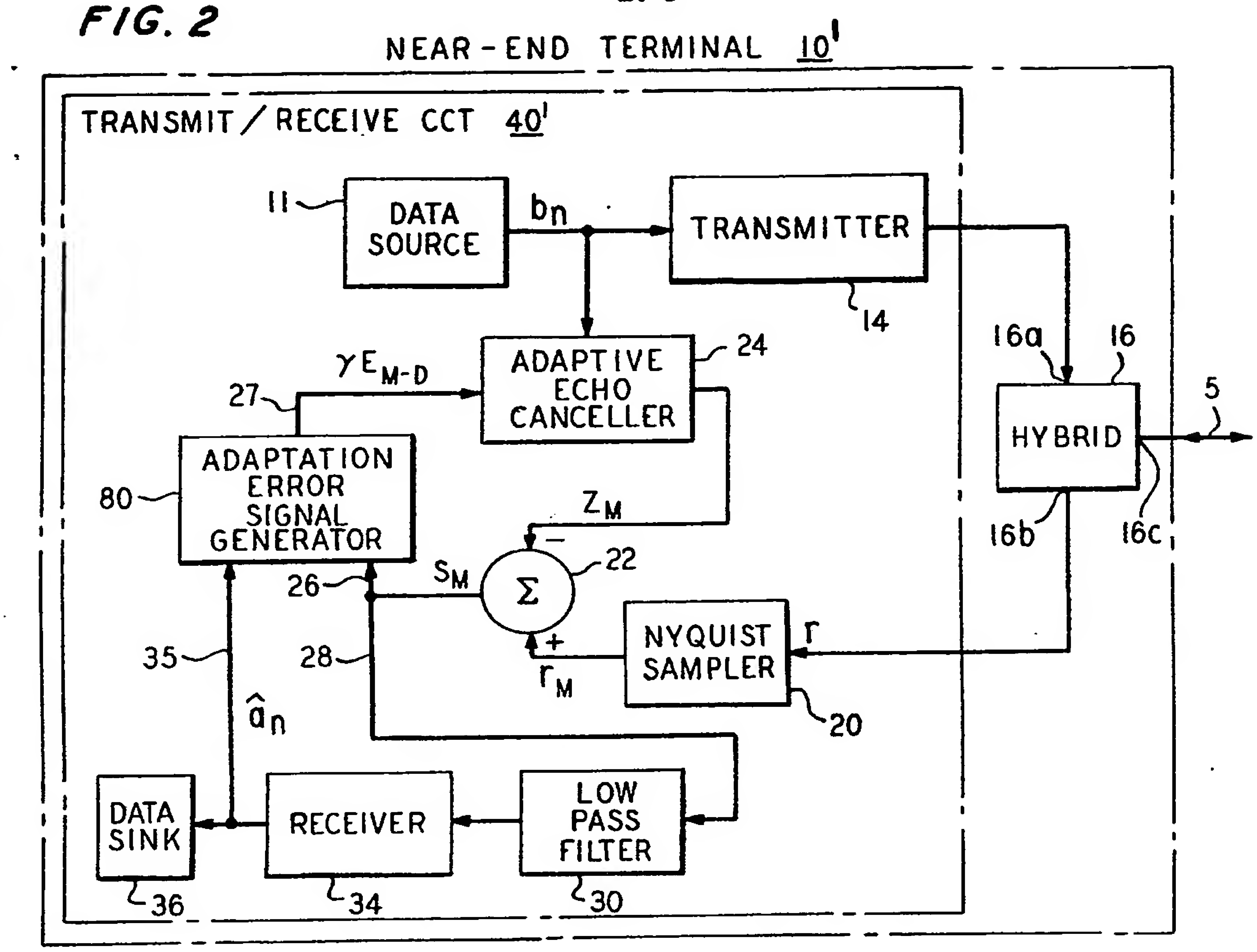

NEAR-END TERMINAL 10'
TRANSMIT / RECEIVE CCT 40'
11
DATA SOURCE
b_n
TRANSMITTER
14
16a
16
5
HYBRID
16b
16c
ADAPTIVE ECHO CANCELLER
24
γE_{M-D}
27
ADAPTATION ERROR SIGNAL GENERATOR
80
Z_M
−
S_M
26
Σ
22
+
r_M
NYQUIST SAMPLER
r
20
35
28
$\hat{a}_n$
DATA SINK
RECEIVER
LOW PASS FILTER
36
34
30

FIG. 3

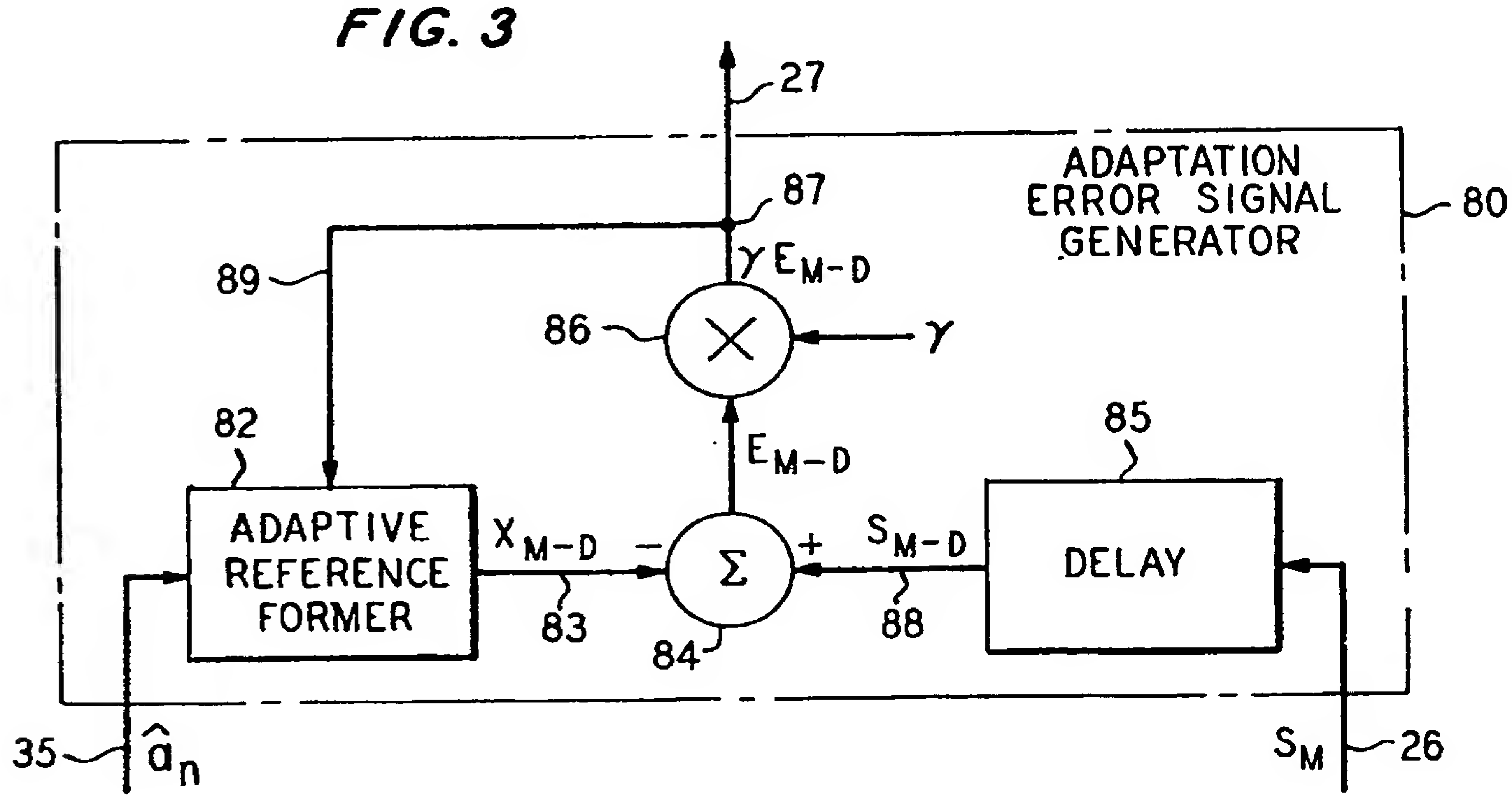
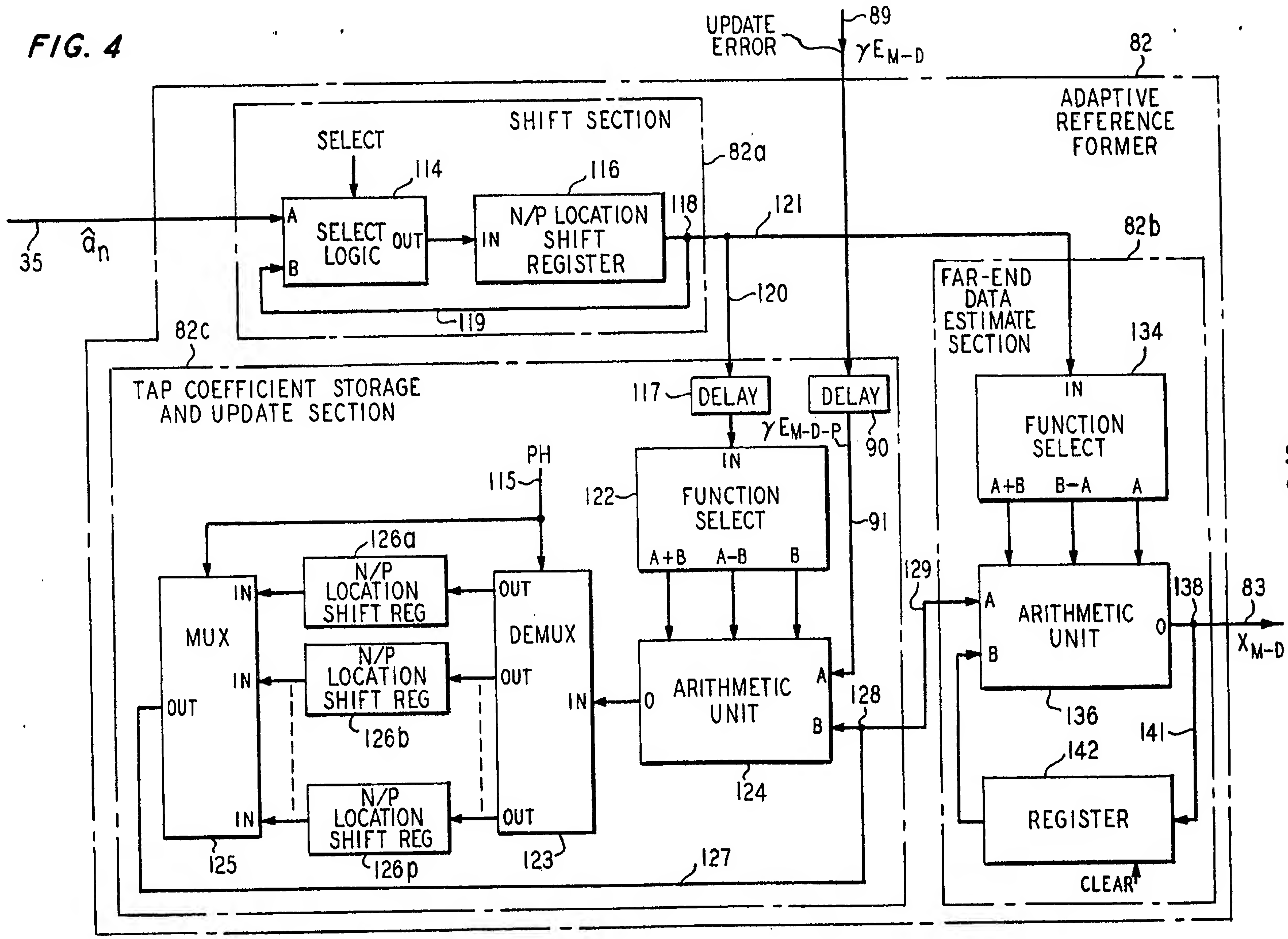

27
87
ADAPTATION ERROR SIGNAL GENERATOR
80
89
γE_{M-D}
86
γ
82
85
E_{M-D}
ADAPTIVE REFERENCE FORMER
X_{M-D}
−
Σ
+
S_{M-D}
DELAY
83
84
88
35
$\hat{a}_n$
S_M
26

FIG. 4


UPDATE ERROR
89
γE_{M-D}
82
ADAPTIVE REFERENCE FORMER
SHIFT SECTION
82a
SELECT
114
116
SELECT LOGIC
A
B
OUT
IN
N/P LOCATION SHIFT REGISTER
118
121
35
$\hat{a}_n$
119
120
82b
FAR-END DATA ESTIMATE SECTION
134
IN
FUNCTION SELECT
A+B
B−A
A
82c
TAP COEFFICIENT STORAGE AND UPDATE SECTION
117
DELAY
DELAY
γE_{M-D-P}
90
PH
115
122
FUNCTION SELECT
A+B
A−B
B
91
126a
N/P LOCATION SHIFT REG
126b
126p
MUX
DEMUX
IN
OUT
ARITHMETIC UNIT
0
128
129
138
83
X_{M-D}
136
141
142
REGISTER
CLEAR
124
125
123
127

SPECIFICATION

Improvements in or relating to signal processing apparatus

This invention relates to signal processing apparatus for the cancellation of echo signals from transmitted digital data and finds application, for example, in the cancellation of echo signals from digital data transmitted over two-way, two-wire telephone transmission channels.

In the field of data communications, it is often advantageous for traffic to be carried over a single communication line (link, channel) in two directions simultaneously, that is, the traffic is full-duplex. A typical transmission medium is a two-wire telephone channel within the public switched direct-distance-dialing (DDD) network. The passband of such a two-wire channel extends from approximately 300 to 3000 hertz. For full-duplex data transmission the available bandwidth can be divided in half, with each half being allocated to a particular transmission direction. However with this method, accurate data transmission can only be achieved at half the rate that could be achieved in one-way (half-duplex) transmission. One way to increase the full-duplex data rate is to use two physically separate two-wire lines, with each line carrying a full bandwidth one-way signal in a respective one of the two transmission directions. This is referred to as a four-wire channel.

Alternatively, high speed, full-duplex transmission can be carried out over a single two-wire channel by using hybrid coupling networks. These networks, positioned at both the so-called near and far ends of the two-wire channel, accept a four-wire signal and convert it into a two-wire signal for transmission over a two-way, two-wire telephone channel. For optimally interference-free transmission, the impedance of the port of the hybrid which interfaces with the channel must exactly match the impedance of the two-wire channel. In practice, however, this is seldom possible.

Specifically, the switched nature of the DDD network means that a large number of communication channels of differing impedance are connected over time to the hybrid. Because the hybrid is designed to operate over as many differing communication channels as practicable, there is generally a mismatch between the hybrid and the channel. Such a mismatch causes a portion of the signal which was transmitted from the near end to be reflected from the channel/fare-end hybrid connection point back into the channel. As in voice transmission, this distant reflected signal is referred to as echo. A data receiver is typically unable to distinguish between data from the far end and the echo of data from the near end. Thus, there is a potential for the near-end receiver to erroneously interpret the echo reflected from the far end as far-end data.

This problem can be handled through the use of echo cancellers. These latter produce a signal which is essentially a replica of the echo component present in an incoming signal, i.e., the signal applied from the two-wire channel to the near-end hybrid. Specifically, each of a predetermined number of previous consecutive symbols in the transmitted signal, in addition to being transmitted, is stored in the echo canceller. Each such symbol is multiplied therein by a respective tap coefficient. The resulting products are summed to produce the replica signal. A resultant subtantially echo-free signal, hereinafter referred to as an echo compensated signal, is obtained by subtracting the replica signal from the incoming signal. The echo compensated signal is applied to a data receiver, which, after processing such as equalisation and demodulation, forms decisions as to the values of the transmitted data symbols.

In general, the echo cancellation process is not perfect. Rather the echo compensated signal may contain an uncancelled echo component. It may also contain a far-end data component as described more fully below. In either case, the magnitude of the uncancelled echo component is indicative of the current effectiveness of the echo cancellation process. A large uncancelled echo component means that the replica signal is an inaccurate replication of the echo component sought to be cancelled. In so-called adaptive echo cancellers, the echo compensated signal is advantageously used as an error signal in response to which the values of all of the tap coefficients are adaptively updated in such a way that the uncancelled echo component is minimised. This assures that the replica signal continuously and, to the extent possible, accurately duplicates the echo component present in the incoming signal, even if the characteristics of the channel change.

The arrangement taught in U.S. patent 4,087,654 is illustrative of so-called baud rate adaptive echo cancellers. In these structures, sampling of the incoming signal, replication of the echo component and echo cancellation all occur at the baud (symbol) rate. Although possessing structural simplicity, these cancellers are highly sensitive to variations in the synchronous timing between the near-end transmitted signal, which is used to define the echo signal replica, and the received data, whose timing is determined at the far end. Moreover, the echo-compensated signal is available to the receiver only at the baud sampling rate. This severely restricts the receiver's ability to accurately recover timing from the far-end signal.

Alternatively, canceller operation at the Nyquist rate has been suggested. Nyquist sampled schemes, which alleviate the above-described timing problem, are exemplified in U.S. patent 4,131,767 and S. B. Weinstein in "A Passband Data-Driven Echo Canceler for Full-Duplex Transmission on Two-Wire Circuits", *IEEE Transactions on Communications,* Vol. COM-25, No. 7, July 1977, pages 654-666, and by K. H. Mueller in "A New Digital Echo Canceler for Two-Wire Full-Duplex Transmission", *IEEE Transactions on Communications,* Vol. COM-24, No. 9, September 1976, pages 956-962. In contrast to baud rate cancellers. Nyquist rate cancellers perform sampling of the incoming signal, each replica generation and echo cancellation all at the Nyquist rate. Tap coefficient adaptation in the Nyquist arrangements is satisfactory in full-duplex systems during intervals

of one-way transmission. However, adaptation is unreliable during intervals of double talk, or two-way transmission, i.e., the simultaneous transmission of far-end and near-end data. These problems arise because the echo compensated signal which feeds the adaptive structure contains not only the uncancelled echo component during double-talk intervals, but also a far-end data component. The far-end data is uncorrelated with respect to the echo. Adaptation and, hence, echo replication generation in response to this signal are thus either unreliable and inaccurate, or is very slow. Thus erroneous data recovery may result. (Baud rate structures are unaffected by these problems because the error signal used to update the echo canceller tap coefficients is taken from a different point in the system, where the far-end data has been determined, and hence has been subtracted out. As such, the error signal is not corrupted by the presence of far-end data.)

Prior art solutions to the above-mentioned problems with Nyquist cancellers include the use of a double-talk detection circuit to halt adaptation and freeze the tap coefficients to their pre-double-talk values for use during the double-talk intervals – see, for example, U.S. patent 3,499,999. Alternatively, as disclosed by Weinstein in the above-cited paper, a running average of a predetermined number of prior coefficient values for each tap can be used in place of the adaptive coefficients during double-talk intervals. While these solutions stabilise system operation, echo cancellation during the double-talk intervals is potentially inaccurate. This is due to the inability of the tap coefficients to adjust during the double-talk intervals to changes in the echo channel impulse response occurring during those intervals.

According to one aspect of this invention apparatus for processing samples of an incoming signal representing a train of data symbols, the samples having data components and echo components, includes means operative in response to adaptation error signals for generating replicas of the echo components, means for combining each sample with the replica of its echo component to produce echo compensated signals and for forming decisions as to the values of the individual data symbols in response to the echo compensated signals, means operative in response to the decsions for forming signals which are estimates of the data components of the samples, and means for generating the adaptation error signals in response to the estimates, samples and replicas.

The estimate-forming means may include means for linearly combining the decisions to form the estimate signals. The estimate-forming means may serve to perform the linear combining by multiplying the decisions by respective coefficients and summing the resulting products. Each adaptation error signal may be substantially equal to an error signal multiplied by a predetermined parameter, the error signal being derived from a respective estimate signal, its associated sample, and the replica of the echo component of that sample. The estimate-forming means may include means for updating values of the coefficients in response to said error signals. The updating means may serve to update the value of each coefficient in response to the product of a said error signal and a predetermined parameter.

the updating means may serve to update the value of each coefficient in response to the product of a said error signal and the decision with which that coefficient was multiplied.

A transmission system may include a near-end terminal and a far-end terminal, the near-end terminal being adapted to transmit to the far-end terminal over a two-way communication path near-end data signals representing near-end data symbols and to receive over the line from the far-end terminal far-end data signals representing far-end data symbols, means at the near-end terminal for producing at at least the Nyquist rate samples of received far-end data signals, the samples having data components and echo components, and apparatus according to the invention for processing the samples.

According to another aspect of this invention a method of processing samples of an incoming signal representing a train of data symbols, the samples having data components and echo components, includes generating in response to adaptation error signals replicas of the echo components, combining each sample with the replica of its echo component to produce echo compensated signals, forming decisions as to the values of the individual data symbols in response to the echo compensated signals, forming in response to the decisions signals which are estimates of the data components of the samples, and generating the adaptation error signals in response to the estimates, samples and replicas.

The invention provides a solution by substantially removing the far-end data component from the echo-compensated signal prior to its application as an error signal to the adaptive echo cancelling structure. This function is illustratively provided by what is hereinafter referred to as an adaptive reference former.

Specifically, the adaptive reference former processes a predetermined number of previous receiver decisions to generate at the Nyquist rate an estimate of the far-end data component present in the echo compensated signal. This estimate is, more particularly, a linear combination of the previous receiver decisions, and is generated by multiplying each of the previous receiver decisions by a respective tap coefficient and combining the resulting products. This generated estimate of the far end data is used to generate the adaptation error signal, the value of which is equal to the difference between the echo compensate signal and the estimate of the far-end data component. This error signal rather than the echo compensated signal is used as the error signal for the adaptive echo canceller. Consequently, echo canceller tap coefficient adaptation is carried out solely in response to uncancelled echo components. This allows for consistently stable and accurate echo cancellation during both double talk and one-way transmission.

The adaptation error signal may be fed back to the adaptive reference former as an update error signal for use in adaptively updating the tap coefficients of the adaptive reference former. This ensures that the

estimate of the far-end data continuously and accurately feflects the far-end of data component present in the incoming signal.

The invention will now be described by way of example with reference to the accompanying drawings, in which:

FIG. 1 is a block diagram of a prior art full-duplex, two-wire digital data transmission system having Nyquist sampled echo cancellation;

FIG. 2 is a block diagram of a Nyquist sampled data terminal embodying the invention;

FIG. 3 is a block diagram of the circuitry within the terminal of FIG. 2 for generating an adaptation error signal; and

FIG. 4 is a block diagram of the adaptive reference former used in the circuitry of FIG. 3.

FIG. 1 depicts a full-duplex digital data transmission system of a type known in the art. In essence this system comprises a two-wire communication link 5 connecting two data terminals, a near-end terminal 10 and a far-end terminal 13. Communication link 5 is illustratively contained within the public switched DDD network, although the invention is equally applicable to other types of communication links, e.g., customer loops. Communication link 5 is a two-way link, that it, it carries data signals from each of the two terminals to the other. Terminals 10 and 13 are of the general type shown and described in the above-cited U.S. patent 4,131,767. Both terminals are, illustratively, identical in structure and operate in the same manner. Hence, the ensuing discussion is substantially limited to near-end data terminal 10.

Terminal 10 comprises transmit/receive circuitry 40 and hybrid 16. Circuitry 40 includes a transmission section which contains data source 11 and transmitter 14. Data source 11 produces a baseband stream of near-end data symbols b_n, $n = 0, 1, 2, \ldots$. The subscript n advances at the baud rate. Symbols b_n are applied to transmitter 14 for conventional shaping and modulation.

The transmission section, as well as the reception section, to be described shortly, interfaces with hybrid 16. The latter permits the connection of a pair of two-wire lines, i.e., a four-wire line, to two-way, two-wire communication link 5. Specifically, the hybrid contains three two-wire ports 16a, 16b and 16c. The outgoing signal, i.e., the output of transmitter 14, is applied to two-wire port 16a via two-wire line 18. Hybrid 16 routes this signal to communication link 5 via port 16c. An incoming signal from the far end, on the other hand, appearing on communication link 5 and incident at port 16c, is routed by hybrid 16 to port 16b. From there the incoming signal, r, representing a train of far-end data symbols, is fed over a separate two-wire line 19 to the reception section of near-end data terminal 10. Similarly, far-end hybrid 15 connects transmit/receive circuitry 17 (which is similar to circuitry 40) to port 15c and communication link 5 through a pair of two-wire lines appearing at ports 15a and 15b.

For optimally interference-free transmission, the output impedance of both near-end hybrid 16 and far-end hybrid 15, must exactly match the impedance of communication link 5. However, in practice, this is seldom possible. For example, in the switched DDD network, a large number of differeing communication links are connected over time between hybrids 15 and 16. Because the hybrids are designed to operate over as many differing communication channels as practicable, an impedance mismatch generally occurs, for example, between far-end hybrid 15 and communication link 5. This causes a sizeable portion of the transmitted near-end signal incident at far-end hybrid 15 to be reflected back into communication link 5 as echo. After a finite time interval, the echo appears at port 16c of a near-end hybrid 16. The reception section of near-end data terminal 10 is unable to distinguish between the incoming data and the echo. However, the inclusion in the reception section of echo canceller 24 (to be discussed shortly) prevents the echo from interfering with the data recovery process.

As previously noted, incoming signal r received from communication link 5 is routed through hybrid 16 via port 16b to the reception section of data terminal 10. Therein this signal is first applied to Nyquist sampler 20. The latter finely samples signal r at at least the Nyquist rate, i.e., a rate equal to at least twice the highest possible frequency present in the incoming signal. For purposes which will become apparent later, the Nyquist rate is illustratively an integer multiple, P, of the baud rate. Sample r_M is one such resulting sample, i.e., the M^{th} sample of a stream of samples of the incoming signal. Subscript M advances at the Nyquist rate. In the general case, signal r comprises both far-end data and echo signals. Thus a portion of the magnitude of sample r_M is due to far-end data and another portion is due to echo. These portions of sample r_M will be respectively referred to hereinafter as the far-end data component and the echo component. As the result, for example, of Nyquist sampling, inter-symbol interference and other distortion, it should be appreciated that the value of the data component of sample r_M of the incoming signal does not reflect the value of any particular transmitted symbol.

The problem to which the present invention is directed will now be illustrated by first assuming that at any one time, only one-way communication is carried over communication link 5, i.e., double talk is precluded. Furthermore, hybrid 16 is assumed to be leak-free, i.e., the outgoing transmitted signals applied to port 16a will not travel through the hybrid and appear at port 16b.

Under these conditions, sample r_M comprises solely a far-end component or solely an echo component. During periods of reception, for example, sample r_M comprises only a far-end data component, i.e., it is echo-free. Sample r_M is applied to combiner 22 wherein it is subtractively combined with echo replica signal z_M, the latter being the M^{th} one of a stream of echo replica signals provided by adaptive echo canceller 24 on lead 21. More particularly, echo replica signal z_M is an estimate by adaptive echo canceller 24 of the echo component of sample r_M. Since that component is, by assumption, zero, echo replica signal z_M is also zero. Thus sample r_M passes substantially unchanged through combiner 22. The output of combiner 22 is a stream of echo compensated

signals, S_M being the M^{th} one of said stream. In this case, echo compensated signal S_M is substantially equal to the far-end data component of sample r_M. The echo compensated signal is applied over lead 28 to low-pass filter 30 which reconstructs a continuous wave therefrom. The filter output, in turn, passes into receiver 34 where it may be sampled, e.g., at the baud rate, further filtered (equalised) to combat intersymbol interference, and quantized to produce decisions $\hat{a}_n$, $n = 0, 1, 2, \ldots$, as to the value of the n^{th} transmitted far-end symbol a_n. Decision $\hat{a}_n$ is applied to data sink 36.

Echo compensated signal S_M is also fed back as an error signal over lead 26 to adaptive echo canceller 24, as discussed more fully below. However, as long as no data symbols are provided by source 11, echo canceller 24 maintains the value of echo replica signal z_M at zero.

Alternatively, during periods of one-way transmission by terminal 10 (again assuming no double-talk), sample r_M comprises solely the echo component produced by the near-end transmitted signal reflecting off the impedance mismatch at the channel/far-end hybrid connection point. Echo replica signal z_M is now non-zero. More specifically, echo canceller 24 generates echo replica signal z_M by operating on a predetermined number of prior consecutive symbols within the data sequence produced by data source 11. These symbols are stored within the echo canceller in a transversal structure. Physically this structure can be, for example, an analog delay line, a shift register or a random access memory. The echo canceller generates a linear combination of prior consective symbols by multiplying each individual symbol by a respective tap coefficient. The resulting products are summed together to produce echo replica signal z_M. Since far-end terminal 13 is not transmitting at this time, echo compensated signal S_M solely comprises an uncancelled echo component. As previously mentioned, signal S_M is fed back over lead 26 as an error signal to echo canceller 24. In response to this error signal, the values of the tap coefficients are adaptively updated to ensure that the echo replica signal, to the extent possible, accurately duplicates the echo component of sample r_M. In this manner, the uncancelled echo component remaining in the echo compensated signal is minimized.

While the arrangement of FIG. 1 performs satisfactorily during one-way operation as just described, it possesses serious drawbacks for two-way operation, i.e., during intervals of double-talk. Specifically, whenever terminals 10 and 13 transmit concurrently, echo of the near-end transmitted data exists on communication link 5 simultaneously with the far-end data transmitted by far-end terminal 13. Thus the error signal applied to echo canceller 24 over lead 26 contains not only an uncancelled echo component but also a far-end data component. This error signal is thus corrupted by the far-end data component. The echo canceller is unable to distinguish between the echo component and the far-end data component. Furthermore, the far-end data is uncorrelated with respect to the echo. Hence adaptation is either unreliable and inaccurate or is very slow. Thus improper echo cancellation may result.

The present invention seeks to provide accurate, stable and reliable adaptation and echo cancellation during periods of double-talk by substantially removing the corrupting far-end data component from the echo-compensated signal to generate an adaptation error signal. This adaptation error signal is equal to a combination of the echo replica signal Z_M, sample r_M and an estimate (discussed below) of the far-end data component associated with sample r_M. The adaptation error signal, rather than the echo-compensated signal, is applied as an error signal to the adaptive echo cancelling structure.

Referring now to FIG. 2, a data terminal 10' differs basically from the prior art terminal 10 in that transmit/receive circuitry 40' in the former includes adaptation error signal generator 80. The adaptation error signal generator accepts as input and processes both the receiver decisions appearing on lead 35 and echo compensated signal S_M appearing on lead 26. The output, appearing on lead 27, is a stream of adaptation error signals of which YE_{M-D} is the $(M-D)^{th}$ one of said stream. The remaining elements of terminal 10' are similar to and carry the same reference numbers as the corresponding elements in terminal 10.

FIG. 3 details the constituent circuit blocks of adaptation error signal generator 80. Specifically, receiver decisions, e.g., decision $\hat{a}_n$, are applied to adaptive reference former 82. The decisions are processed in the adaptive reference former to produce on lead 83 a stream of estimates, with each estimate approximating the far-end data component of a particular one of the samples of the incoming signal applied to combiner 22. There is a processing delay of D Nyquist intervals from the output of combiner 22 to the output of receiver 34. Thus, at the point in time that echo compensated signal S_M appears on lead 26 (FIG. 2), the signal appearing on lead 83 is an estimate X_{M-D} of the data component of the echo compensated signal generated D Nyquist intervals earlier, i.e., signal S_{M-D}. Generator 80 includes a delay 85, which imparts a delay of D Nyquist intervals to the echo compensated signals extended thereto on lead 26. Thus, delayed echo compensated signal S_{M-D} appears on output lead 88 of delay 85 at the same time that estimate X_{M-D} appears on lead 83. The latter is subtracted from the former in combiner 84 to produce error signal E_{M-D}.

Error signal E_{M-D}, of course, reflects not the current echo cancellation error, but rather, that which existed D Nyquist intervals in the past. That signal can nonetheless be used as the basis for updating the tap coefficients employed in echo canceller 24. In particular, error signal E_{M-D} is multiplied in multiplier 86 by a parameter Y to produce adaptation error signal YE_{M-D}. Parameter Y, which is much less than unity, is selected to ensure smooth, stable convergence, i.e., minimal under- and over-shooting in the response of adaptive echo canceller 24 to step changes in the characteristics of communication link 5. (In the present illustrative embodiment, the value of parameter Y is fixed; however, in other embodiments it may be advantageous to dynamically adjust the value of Y to equal the reciprocal of the mean squared value of all of the data symbols stored in the

adaptive reference former.)

As described more fully below, adaptive reference former 82 receives an update error signal for purposes of updating tap coefficients used therein. Like the adaptation error signal, the update error signal is also equal to the product of error signal E_{M-D} with a predetermined parameter. Thus, the adaptation and update error signals are proportional to one another. In this embodiment, more particularly, the two are equal. Thus, as shown in FIG. 3, adaptation error signal YE_{M-D}, in addition to being applied to adaptive echo canceller 24 over lead 27, is fed back to adaptative reference former 82 over lead 89.

It may be desired, however, for the update error signal applied to adaptive reference former 82 to be different from the adaptation error signal, thereby providing the reference former and echo canceller with different error sensitivities. This could be accomplished, for example, by taking lead 89 from the output of a second multiplier (not shown) rather than from the output of multiplier 86. This second multiplier, like multiplier 86, would receive an input from the output of combiner 84 but would multiply that output by a different parameter.

As depicted in FIG. 4, adaptive reference former 82 comprises shift section 82a, far-end data estimate section 82b, and tap coefficient storage and update section 82c. Operation within each section takes place within a processing cycle, the duration of which is no greater than a Nyquist interval. This allows a new estimate of the far-end data component to be produced for each output of Nyquist sampler 20.

The Nyquist rate is illustratively P times the baud rate, where P is an integer. Thus, P far-end data component estimates must be produced within any baud interval. Only one receiver decision is applied to the adaptive reference former during each baud interval. Therefore adaptive reference former 82 forms each of the P estimates as a respective linear combination of a common set of $\frac{N}{P}$ previous receiver decisions, each linear combination being formed using a particular one of P sets of $\frac{N}{P}$ tap coefficients, N being a selected number, equal to the number of Nyquist intervals over which the decisions stored in adaptive reference former 82 extend.

More specifically, shift section 82a comprises select logic 114 and $\frac{N}{P}$ location shift register 116. Together these two units function as a right circular shift register of length $\frac{N}{P}$. At the occurrence of each receiver decision e.g., $\hat{a}_n$, on lead 35, a select signal from timing circuitry (not shown) within terminal 10' is applied to select logic 114. This causes the receiver decision $\hat{a}_n$ to pass through select logic 114 to the input of shift register 116. However, at all other times, select logic 114 applies the output of shift register 116 occurring on lead 119 to the input of the same shift register. Hence, at all times, shift register 116 contains the most recent decision $\hat{a}_n$ and $\frac{N}{P}-1$ previous receiver decisions. Within shift register 116, these decisions are ordered in terms of occurrence. For example, just after the select logic admitted a new decision, the "oldest" decision, i.e., $\hat{a}_{n-(\frac{N}{P}-1)}$ is stored at the rightmost (output) location, and the next oldest decision is stored one location to the left, and so forth. Moreover, the contents of shift register 116 are shifted $\frac{N}{P}$ times during each Nyquist interval (processing cycle), such that within each processing cycle, a sequence of the $\frac{N}{P}$ stored receiver decisions appears at junction 118. Thus, within each baud interval, this sequence of $\frac{N}{P}$ ordered past receiver decisions is applied P times to junction 118. Furthermore, register 116 is shifted one location to the right just before each new receiver decision is applied thereto. From junction 118, the complete sequence is applied through leads 121 and 120 to sections 82b and 82c, respectively.

Far-end data estimate section 82b utilises the i^{th} one of P sequences of tap coefficients during the i^{th} processing cycle to produce far-end data estimate X_{M-D}. The following equation governs the operation of this section:

$$X_{M-D} = \sum_{K=1}^{N/P} W_n^K(i)\hat{a}_{n-K+1} \text{ for } i = \text{mod}_P(M) \qquad (1)$$

In this equation, $W_n^K(i)$ represents the current value of the K^{th} coefficient in the i^{th} one of the P coefficient sequences. The value of the modulo function $\text{mod}_P(M)$ is equal to the remainder of the quotient $\frac{M}{P}$ e.g., i = 3 for M = 11, P = 4. Thus, each far-end data estimate formed during a given baud interval is seen to be a linear combination of a common, i.e., the same, set of $\frac{N}{P}$ past receiver decisions, each linear combination being formed with a respective one of P sets of $\frac{N}{P}$ tap gain coefficients.

Specifically, during the first Nyquist interval within the n^{th} baud interval, the common set of $\frac{N}{P}$ previous receiver decisions $\hat{a}_{n-K+1}$, $K = 1, 2, \ldots, \frac{N}{P}$ is linearly combined using the first sequence of tap gain coefficients i.e., $W_n^K(1)$ $k = 1, 2, \ldots, \frac{N}{P}$ to produce the first of P far-end data component estimates. Throughout the succeeding Nyquist intervals within the same baud interval, the same set of $\frac{N}{P}$ receiver decisions is combined with a different set of $\frac{N}{P}$ tap gain coefficients to produce further estimates of the far-end data. This process continues until the common set of $\frac{N}{P}$ receiver decisions has been processed with all P sets of $\frac{N}{P}$ tap gain coefficients.

Far-end data estimate section 82b comprises function select 134, arithmetic unit 136 and register 142. In the present illustrative embodiment, each receiver decision $\hat{a}_n$ is ternary, i.e., can take on one of three

values: +1, −1 or 0. To calculate each term in the summation given by equation (1) above, function select 134 ascertains the value of each receiver decision on lead 121 and, depending upon the particular value, instructs arithmetic unit 136 to perform a particular operation on the signals presented to the latter's A and B inputs. More specifically, if the receiver decision is +1, arithmetic unit 136 is instructed to add the values presented to its A and B inputs. If the receiver decision is −1, arithmetic unit 136 is instructed to subtract the value presented to its A input from that presented to its B input. In either case, the result is applied to output 0. Thirdly, if the receiver decisions is zero, arithmetic unit 136 merely applies the value presented to its B input to output 0. The signal applied to input B is the output of register 142 and that presented to input A is the sequence of tap coefficients $W_n^K(i)$ $K = 1, 2, \ldots, \frac{N}{P}$. Register 142 is used to temporarily store the result produced by arithmetic unit 136 and apply it to the latter's B input for use in the subsequent calculation. The contents of register 142 are set to zero at the beginning of each processing cycle by the application of a clear signal (generated from circuitry not shown). Thus by temporarily storing successive results, register 142 contains a running total of the results of all the prior operations performed during a Nyquist interval in the course of calculating equation (1). At the conclusion of each processing cycle, within which $\frac{N}{P}$ decisions and tap coefficients have been processed, the output signal of arithmetic unit 136 which appears at junction 138 and on lead 83 is the estimate X_{M-D} of the far-end data component.

Tap coefficient storage and update section 82c provides and adaptively updates the P tap gain coefficient sequences. In particular, a coefficient is updated by modifying its value by a correction factor equal to the product of an update error signal—which in this embodiment is equal to an adaptation error signal—with a receiver decision.

Specifically, the coefficients in a particular sequence must be updated in response to the particular update error signal which was formed as a result of the use of that sequence in section 82b. Thus the coefficients of the i^{th} sequence could be updated in response to signal YE_{M-D} where, as in equation (1), $i = \mathrm{mod}_P(M)$. However, as will be apparent from the discussion below, the values of the coefficients in the i^{th} sequence are updated in this embodiment before estimate X_{M-D}, and thus signal YE_{M-D}, are formed.

As a result, section 82c updates the coefficients of the i^{th} sequence in response to signal YE_{M-D-P}. The latter is equal to that one of the P adaptation error signals formed in the previous, i.e., $(n-1)^{st}$, baud interval which corresponds to the i^{th} coefficient sequence.

As previously noted, the updating process includes multiplication of the update error signal with a receiver decision. The latter is that decision by which the coefficient being updated was multiplied in the baud interval in which the error signal was formed. In this embodiment, then, the appropriate decision is

$$\hat{a}_{n-K}, K = 1, 2, \ldots \frac{N}{P}.$$

As a consequence of the foregoing, operation of section 82c, i.e., adaptation of the tap coefficients, is governed by the following equation:

$$W_{n+1}^K(i) = W_n^K(i) + YE_{(M-D-P)}\hat{a}_{n-K} \text{ for } \begin{cases} K = 1, 2, \ldots, \frac{N}{P} \\ i = \mathrm{mod}_P(M) \end{cases} \quad (2)$$

From this equation it is seen that a different one of the P sequences of tap coefficients is updated during every processing cycle so that each one of the P tap coefficient sequences is updated during each baud interval.

Tap coefficient storage and update section 82c comprises one-baud delays 90 and 117, function select 122, arithmetic unit 124, demultiplexer 123, shift registers 126a to 126p, and multiplexer 125. Function select 122 operates in a manner similar to function select 134 in section 82b. In particular, function select 122 instructs arithmetic unit 124 to perform one of three operations on its A and B inputs in order to calculate updated tap coefficient $W_{n+1}^K(i)$ according to equation (2). More specifically, depending upon the value, i.e., +1, −1 or 0, of each of the receiver decisions provided from one-baud delay 117, arithmetic unit 124 provides as the value of the updated coefficient the sum of the values of the signals presented to its A and B inputs, the difference between the values of those signals or the value of the signal presented to the B input, respectively. The signal presented to input A via lead 91 is signal YE_{M-D-P}, provided by one-baud delay 90. The signal presented to input B via lead 127 and junction 128 is the value of the tap coefficient $W_n^K(i)$.

Within section 82c, each set of $\frac{N}{P}$-tap coefficients is held in a respective one of P shift registers, 126a, 126b, ... 126p. The value of signal PH, provided on lead 115, indicates which of the P sets of tap coefficients is to be routed through demultiplexer 123 and multiplexer 125. The value of signal PH is incremented during each successive processing cycle and is reset at the beginning of each baud interval. In this manner, a different set of $\frac{N}{P}$-tap coefficients is selected for updating during every processing cycle, and all P sets are updated during each baud interval.

As will be appreciated by those skilled in the art, the invention can be implemented in various ways in addition to the specific illustrative embodiment described above.

CLAIMS

1. Apparatus for processing samples of an incoming signal representing a train of data symbols, the samples having data components and echo components, including means operative in response to adaptation error signals for generating replicas of the echo components, means for combining each sample with the replica of its echo component to produce echo compensated signals, and for forming decisions as to the values of the individual data

symbols in response to the echo compensated signals, means operative in response to the decisions for forming signals which are estimates of the data components of the samples, and means for generating the adaptation error signals in response to the estimates, samples and replicas.

2. Apparatus as claimed in claim 1 wherein the estimate-forming means includes means for linearly combining the decisions to form the estimate signals.

3. Apparatus as claimed in claim 2 wherein the estimate-forming means serves to perform the linear combining by multiplying the decisions by respective coefficients and summing the resulting products.

4. Apparatus as claimed in claim 3 wherein each adaptation error signal is substantially equal to an error signal multiplied by a predetermined parameter, the error signal being derived from a respective estimate signal, its associated sample, and the replica of the echo component of that sample.

5. Apparatus as claimed in claim 4 wherein the estimate-forming means includes means for updating values of the coefficients in response to said error signals.

6. Apparatus as claimed in claim 5 wherein the updating means serves to update the value of each coefficient in response to the product of a said error signal and a predetermined parameter.

7. Apparatus as claimed in claim 5 or 6 wherein the updating means serves to update the value of each coefficient in response to the product of a said error signal and the decision with which that coefficient was multiplied.

8. A transmission system including a near-end terminal and a far-end terminal, the near-end terminal being adapted to transmit to the far-end terminal over a two-way communication path near-end signals representing near-end data symbols and to receiver over the line from the far-end terminal far-end data signals representing far-end data symbols, means at the near-end terminal for producing at at least the Nyquist rate samples of received far-end data signals, the samples having data components and echo components and apparatus as claimed in any preceding claim for processing the samples.

9. A method of processing samples of an incoming signal representing a train of data symbols, the samples having data components and echo components, including generating in response to adaptation error signals replicas of the echo components, combining each sample with the replica of its echo component to produce echo compensated signals, forming decisions as to the values of the individual data symbols in response to the echo compensated signals, forming in response to the decisions signals which are estimates of the data components of the samples, and generating the adaptation error signals in response to the estimates, samples and replicas.

10. Apparatus for processing a stream of samples of an incoming signal, substantially as herein described with reference to Fig. 2, or Figs. 2 and 3, or Figs. 2, 3 and 4 of the accompanying drawings.

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